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6. AUTHOR(S)

Ray T. Chen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Microelectronics Research Center
Dept. of Electrical & Computer Engineering
University of Texas @ Austin
Austin, TX 78712

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Abstract

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LD-3 polymer directional couplers have the potential use as low-voltage modulators and switches. They can be integrated into module-to-module systems using currently available VLSI fabrication techniques. Modes of channel waveguides are calculated and coupling lengths are determined using BPM_CAD. LD-3 polymer directional couplers are designed and fabricated to operate at 1.3 μm. Waveguide propagation losses, device characterization, demonstration of cross coupling and packaged device pictures are presented in this final report.

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1. INTRODUCTION

Many of today's commercially available electro-optic devices are made from inorganic materials such as lithium niobate. The drawback of such devices is that they cannot be easily integrated with electronic circuitry fabricated on silicon wafers. These difficulties prevent the reduction of the fabrication cost and hence their wide spread use. Compared with their inorganic counter parts, nonlinear-optical (NLO) polymeric materials have several well-recognized advantages such as compatibility with different substrates, ease of fabrication, and possibly low cost. As a result, a lot of NLO polymers have been synthesized in recent years[1,2,3,4,5]. A low-loss waveguide with a large and stable NLO coefficient is needed for a practical device. Polyimide NLO materials offer the best stability; however, the forms that possess an optical nonlinearity have relatively high optical loss (>3dB/cm) and often the case is that the loss and processability remain unreported[2]. Other less-lossy materials do not possess the thermal stability to satisfy commercial or military requirements[6]. Much higher stability can be achieved by crosslinking both of the ends of an NLO chromophore into the polymer network. Although many efforts have been made, only a few NLO materials have achieved long term stabilities near or up to 100 °C[1,2,3,5] and only

one material (LD-3) has a long-term thermal stability satisfying the military requirement of 125 °C[4]. The polymer LD-3 is a thermally crosslinkable NLO polymer consisting of a poly (methyl methacrylate) (PMMA) backbone and an azobenzene-sulfone chromophore. It can be crosslinked using a diisocyanate. We use Dianisidine diisocyanate from Pfaltz &Bauer, Inc. The chemical structure of LD-3 and the diisocyanate are shown in Figure 1.

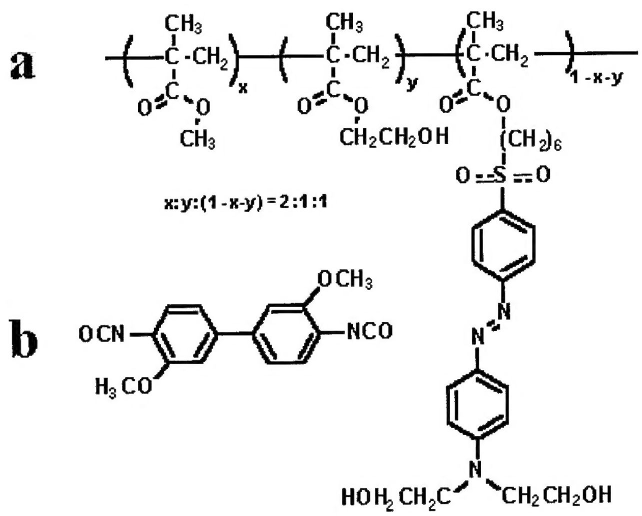


FIG. 1. (a) the LD-3 polymer (b) the diisocyanate crosslinker.

An r33 value of 13pm/V at 633 nm is achieved and a long-term stability at 125 °C is proved through annealing a sample at this temperature for over 1250 hours[7].

2. BPM SIMULATION AND MASK FABRICATION

The first step in the fabrication of the directional coupler is to calculate the modes of the channel waveguides using the beam propagation method. BPM_CAD by OPTIWAVE Corporation is used to calculate the modes of a 1.5 μm by 7 μm channel waveguide. The LD-3 waveguide was first thought to have an index of 1.5463. It was later measured to have an index of 1.59. These first simulations were done with an LD-3 index of 1.5463. The index of the surrounding substrate and cladding material NOA-61 is 1.5409. All these indices are based on an operating wavelength of 1.3 μm. The mode solver predicts the channel waveguide will support only a single mode with an effective index of 1.541187. The field distribution of the mode is saved and used as the input field for the directional coupler simulation. The directional coupler is simulated using two 1.5 μm by 7 μm channel waveguides separated by 10 μm. For this design, the coupling length is determined to be about 8.1 mm as shown in Figure 2.1.

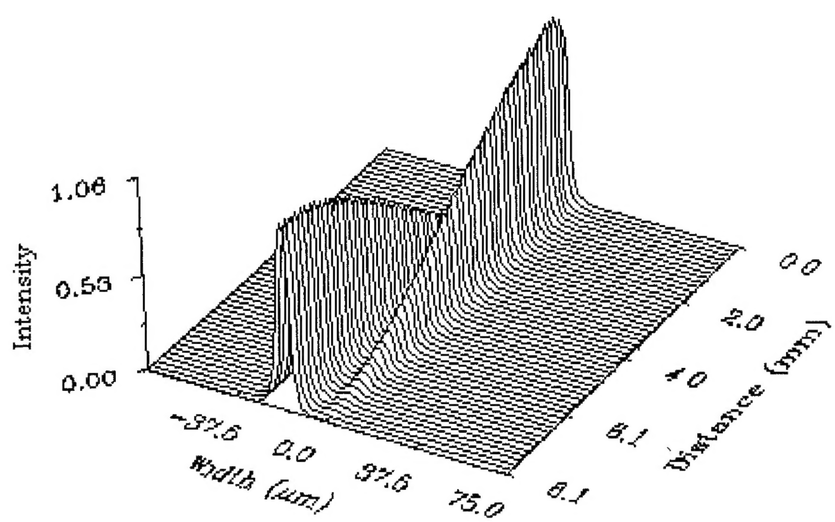


Fig. 2.1. BPM_CAD simulation of the intensity as a function of the width and propagation distance.

From the results of the BPM_CAD simulations, an Autocad drawing is made with a parallel coupling length region of 7.9 mm, a 10 μm channel separation, and a 7 μm channel width. At both the input and output ends of this directional coupler, arcs of 10 mm radius of curvature are designed to facilitate coupling of light into and out of each of the channels. The channels at both the input and output regions are separated by 200 μm. A schematic of the Autocad mask design is shown in Figure 2.2.

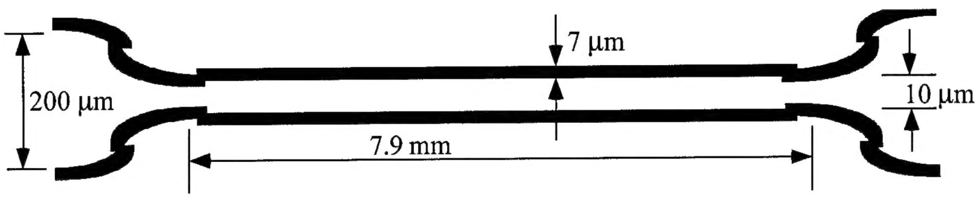


Fig. 2.2. Schematic of the Autocad drawing for the directional coupler.

Using this Autocad file, an image reversed iron-oxide mask is made using an RDI pattern generator. To obtain an image reversed iron-oxide mask, the following steps are taken. AZ5209 photoresist is spin coated onto an iron oxide plate and dried at 90 °C for fifteen minutes. This plate is patterned with the RDI using an exposure time of 0.07 seconds. The plate is then hard baked at 125 °C for seven minutes. Afterwards, the plate is subjected to a UV exposure of two minutes from a Karl-Suss mask aligner. The plate is developed with AZ425

developer for about 30 seconds. Another hard bake at 125 °C for fifteen minutes is done to fix the remaining resist that defines the channel regions. Finally, the plate is submersed in the iron-oxide etchant ME-10 for 20 seconds and then rinsed with DI water and dried.

Another BPM_CAD simulation using an LD-3 index of 1.59 was run for a 1 μm by 3.5 μm channel waveguide. The mode solver calculated an effective index for the first mode to be 1.55682 at 1.3 μm. The field distribution of this mode was then saved and used as the input filed for the directional coupler simulation. The directional coupler was simulated using two 3.5 μm channel waveguides separated by 3.5 μm. For this design, the coupling wavelength was determined to be about 9 mm. Several directional couplers were made on a new mask with different channel separations to accommodate fabrication tolerances. Channels separations of 2 μm, 3.5 μm, and 5 μm were designed, all with channel widths of 3.5 μm and 9 mm coupling length.

3. DEVICE FABRICATION

The following steps are taken in the fabrication of a directional coupler. First, a bottom cladding layer of NOA-61 is spun onto a silicon wafer to form a 3-μm layer. The NOA-61 layer is then cured with UV light. Next, LD-3 is spin coated onto the NOA-61 layer. This results in an LD-3 layer with a thickness of 1.2 μm. The LD-3 layer is liquid contact poled and cured. AZ5209 photoresist is then spun onto the LD-3 layer and patterned using the mask for the directional

coupler. The sample is then developed with AZ425 developer and reactive ion etched to define the channel waveguide regions. A top NOA-61 cladding is then applied to the sample and cured. The silicon wafer is then scribed and cut, so that the ends of the device are at the edges of the wafer. The input and output ends are then polished using a Beuhler polisher with diamond abrasive films of various grits. First, a 9 μm diamond abrasive film is used for ten minutes at 90 revolutions per minute. Then an abrasive film of 6 μm grit is used for seven minutes at 70 RPM. Next, a film of 3 μm grit is used for three minutes at 40 RPM. Finally, a 1 μm grit film is used for one minute at 30 RPM. For all the films, a Kimwipe® is used to clean the abrasive film of the residue being removed from the sample. The polishing resulted in a smooth interface for coupling. A schematic of the cross section of the input to the directional coupler is shown in Figure 3.1.

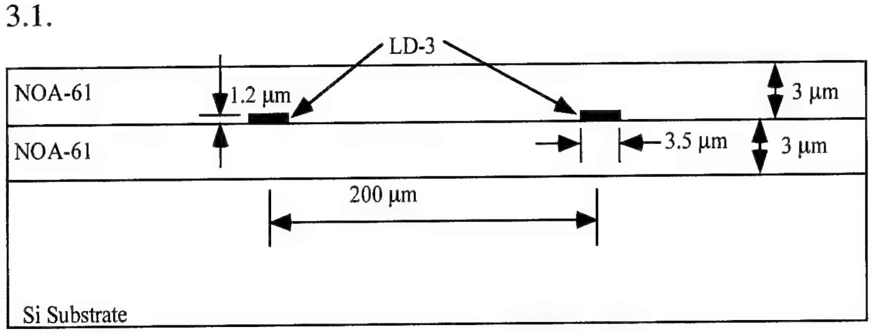


Fig. 3.1. Schematic of cross section of the input.

A photograph of the output end of a directional coupler device was taken using a digital SPOT® camera. The channels in this earlier sample have a center-to-center separation of 18 μm and are the dark colored trapezoids in the picture.

The right channel is outlined with a white trapezoid to assist in identifying the LD-3 channel waveguides. The photograph is shown in Figure 3.2.

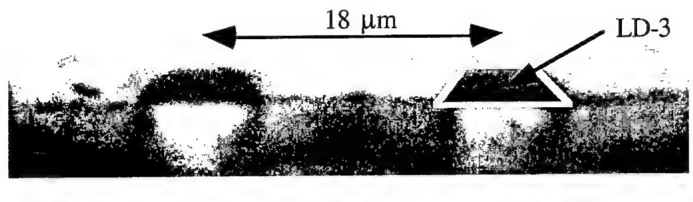


Fig. 3.2. Photograph of output cross section

A photograph of one of the outputs of a 3.5 μm channel is shown in Figure 3.3. The LD-3 channel is the dark outlined trapezoidal structure in the middle of the figure. In Figure 3.4, four channels from two directional couplers are seen as black spots. As can be seen in this photograph, the top cladding is about 30 μm. For an active device, most of the top cladding would be reactive ion etched before a top electrode would be fabricated. The distance from the top of the LD-3 channel to the top electrode should be about 3μm.

Fig. 3.3 Cross-sectional view of a 3.5 μm channel.

Fig. 3.4 Four channels from two directional couplers.

As mentioned earlier, for the fabrication of an active device, electrodes need to be patterned above and below the channel waveguide regions. This is accomplished by first evaporating a metal such as gold or aluminum onto the silicon substrate. The electrode region is then patterned and defined using another mask made specifically for the electrode structure. The spin coating of the bottom NOA-61 layer, LD-3 layer, and top NOA-61 layer are all done as previously described. Finally, a top metal layer of gold or aluminum is evaporated and patterned onto the top NOA-61 layer. For an active device, the cladding regions should be as thin as possible, so that lower modulation voltages can be used. A schematic of an active device is shown in Figure 3.5.

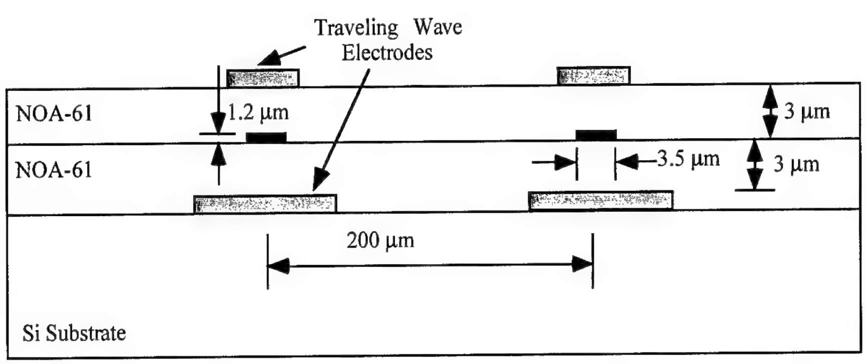


Fig. 3.5. Schematic of cross section of an active device.

4. COUPLING SETUP AND RESULTS

The directional coupler sample is mounted between two microscope objective lenses in a butt-coupling arrangement as shown in Figure 4.1.

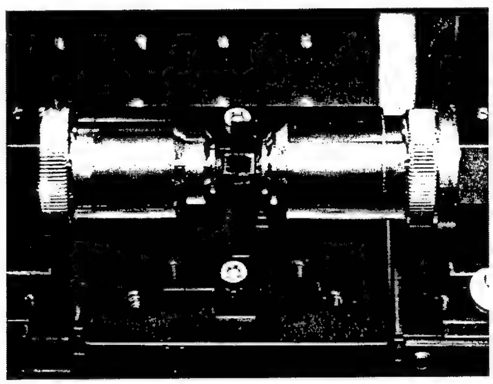


Fig. 4.1. Butt-coupling setup.

Output from a 1.3 μm Santa Fe Nd:YAG Laser is coupled into the waveguide using a 60_ objective and the light is coupled out using a 40_ objective. The near field pattern is imaged onto a screen about a foot away from the output coupler and viewed with an infrared camera. For our test sample, the input and output taper regions have been removed. Therefore, straight channels 10 μm apart remain as shown in Figure 4.2.

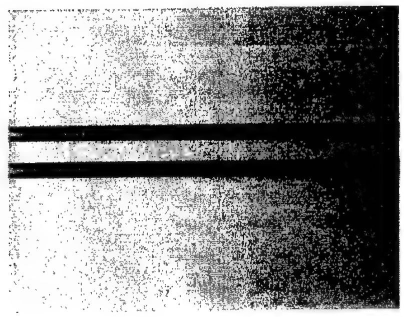


Fig. 4.2. Top view of the parallel channels which are separated by 10 μm.

Only the parallel section of the channel waveguides are used because we first want to show that 1.3 μm light can be successfully waveguided. The laser beam can be coupled into either channel waveguide individually or both channels at the same time due to the narrow separation of the channels. For light coupled into both channel waveguides, Figure 4.3 shows the near field pattern. The pattern is also analyzed with a beam profiler and the results are shown in Figure 4.4.

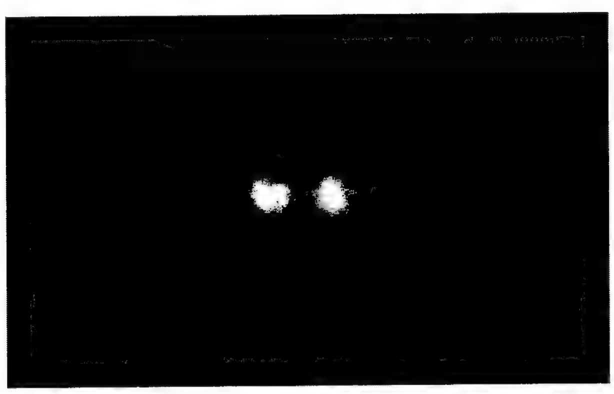


Fig. 4.3. Near-field pattern viewed with an IR camera.

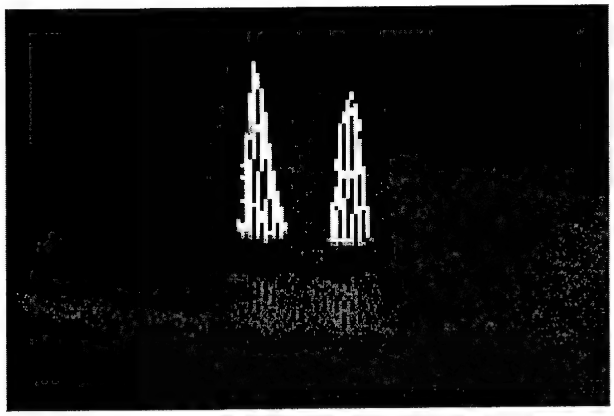


Fig. 4.4. 3-D beam profile.

The first directional coupler devices that were tested had a channel width of 7 μm and a channel separation of 10 μm. Light of 1.3 μm was successfully coupled into these channels, but no cross coupling was observed. There was either a problem with the simulation or with the material data used in the simulation. Turns out that the index of refraction for LD-3 was higher than originally thought. The first BPM_CAD simulations were run using an index of 1.5463 for LD-3 at 1.3 μm. After no coupling was observed, the index of LD-3 was measured in the lab using a prism coupling technique to be about 1.59 at 1.3 μm. This was considerably higher and thus explained the fact that no coupling was observed in the first designs due to the increased confinement in the LD-3 channels. BPM_CAD simulations were then run again using the new index data and it was determined that for 3.5 μm channels separated by 3.5 μm, the coupling length was about 9 mm.

For these new devices with a much narrower channel separation, cross coupling was observed in several directional coupler sets. Although the Autocad drawings were designed and drawn to have a 3.5 μm channel width with a 3.5 μm channel length, the actual sizes of the final devices varied from initial designs. Channel widths were larger than anticipated and channel separations were smaller than designed. Channels separations ranged from no separation to a separation of 2 μm. Figure 4.5 shows the output from various directional couplers.

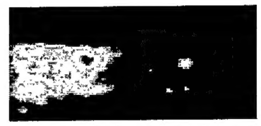
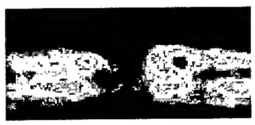
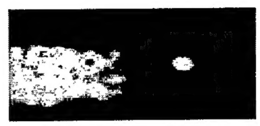
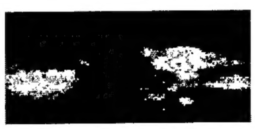
Directional Coupler Set	Looking at the input face, light into ...	
	Left Channel	Right Channel
A1		
A2		
A3		
A4		
B1		
B2		
B3		

Fig. 4.5. Output from directional couplers.

The images are what would be seen if you were looking at the output face of the directional couplers. Directional coupler sets A2 and B2 have no channel separation and are essentially Y-branches. Only directional coupler sets A1, A3, and A4 seem to exhibit any cross coupling. These directional couplers have a channel separation of about 1 μm. B1 and B3 have a channel separation of about 2 μm.

5. CONCLUSION

LD-3 polymer directional couplers are modeled using BPM_CAD. Modes of 7 μm and 3.5 μm channel waveguides are calculated and coupling lengths are determined using this beam-propagation-method software. Masks for the directional couplers are made with the dimensions determined from the simulations. Directional couplers are successfully fabricated with LD-3. Initial testing shows that light is coupled into the channel waveguides and some passive cross coupling is observed.

The next step in making an active directional coupler switch is to put metal electrodes over directional coupler sets A1, A3, and A4. Fabrication tolerances also need to be improved so that what is actually designed can be fabricated. In my samples it was observed that the channel separation at the beginning of the parallel region was not the same as the separation towards the end of the coupling region. These issues in fabrication need to be resolved before an active directional coupler can be made.

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